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THERMAL INSTABILITY OF UNDERGROUND POWER CABLES

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There is a sustained interest in predicting the likelihood of thermal instability in both new and existing underground cable systems. In this report, the mechanism of thermal runaway is reviewed. A rational basis for identifying the potential for thermal instability in various types of soils is proposed. The computer code used in this study to model the heat and moisture migration phenomena is verified by the results of a field thermal stability experiment. The relevance of the factors selected for the identification system is substantiated by the results of a parametric study.

1.0 INTRODUCTION

The performance of underground power cables is critically affected by the thermal properties of the backfill around the cable. Heat generated by an underground cable has to be dissipated through the surrounding soil. The temperature gradients imposed on the soil by the heat dissipation process may induce moisture migration away from the cable. With the continued depletion of soil moisture adjacent to the cable, the thermal resistivity of the soil, which is strongly dependent on its moisture content, can increase. At this stage the cable temperature may reach a value far in excess of its safe operating limit. Ultimately, it may result in cable failure.

When the heat transfer process induces rapid thermal drying of the backfill soil causing the cable temperature to rise rapidly, the cable system is said to be thermally unstable. The term thermal runaway is also used to describe such a phenomenon.

In this report, the mechanism of thermal runaway is reviewed. A rational basis for identifying the potential for thermal instability in various types of soils is proposed. The relevance of the factors selected for the identification system is substantiated by the results of a parametric study.

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The computer code used in this study to model the heat and moisture migration phenomena is verified by the results of a field thermal stability experiment.

2.0 MECHANISM OF THERMAL MOISTURE MIGRATION

Several mechanisms of thermal moisture migration in soils have been suggested by various researchers. On the basis of indirect experimental evidence obtained by Hadley and Eisenstadt/1/ and by Milne and Mochlinski/2/, the thermal moisture migration in a wide range of soils can be idealized into two mechanisms, namely, vapour diffusion through the air-filled pores, and liquid capillary conduction.

Under a temperature gradient, the water in a moist soil evaporates on the warmer side and diffuses through the air-filled voids to the cooler side, where it condenses. The vapour diffused from the warmer side leads to a gradual drying of the soil. This is counteracted by the capillary attraction of the moisture in the liquid phase from the moist side to the drier side, setting up a moisture redistribution in the soil.

Under the heat generation process from the power cable, the two mechanisms of moisture migration interact. If, as a result of this interaction, the liquid and vapour flow are in equilibrium, no further change in the soil moisture occurs. If, on the other hand, the conditions are such that the vapour outflow away from the cable is in excess of the liquid inflow toward the cable, a net loss of moisture in the vicinity of the cable results. Experimental evidence and theoretical justification for this thermal moisture migration in partially saturated soils as related to cable backfills were presented by Adams and Baljet/3/ and Radhakrishna/4/.

3.0 THE THERMAL INSTABILITY PHENOMENON

In Figure 1, the theoretical time-temperature relationship of a line heat source of constant heat flux, buried in an infinite soil medium at a given moisture content, is presented. When the thermal resistivity of the soil is independent of its moisture content, the temperature versus log time curve is linear. When the thermal resistivity of the soil becomes a function of its moisture content, with the occurrence of thermal moisture migration in the soil adjacent to the heat source, the skin temperature versus the log-time curve will become non-linear. Hartley and Black/5/ identified two stages of thermal drying. During the first stage of drying, a general decrease in moisture of the soil is accompanied by a slight increase in thermal resistivity of the soil. The time required to reach this condition is defined by Hartley and Black/5/ as the initial drying time, which corresponds to the time at point A in Figure 1. The corresponding moisture content of the soil is defined by Radhakrishna/4/ as the critical moisture content of the soil. The second stage of drying is characterized by an increase in drying rate and a rapid increase of thermal resistivity. Point B in Figure 1 corresponds to the time at which the soil adjacent to the heat source completely dries and the skin

temperature of the heat source versus the log-time curve once again becomes linear and the slope of which is determined by the dryout thermal resistivity of the soil.

Radhakrishna et al/6/ suggested the use of critical moisture content as a criterion to determine the thermal instability of cable systems. They demonstrated that the thermal instability of a cable system occurs when the moisture content of the soil is below its critical moisture content. In Figure 2, the critical moisture content of three soils are indicated by arrows. This criterion provides the necessary condition for thermal instability.

From a theoretical study, Hartley and Black/5/ showed that the time for the initiation of thermal instability of a cable system can be calculated based on the time for the initiation of thermal instability of a small diameter cylindrical heat source buried in the same soil. The purpose of using a smaller diameter heat source is to shorten the required testing time. The application of this method for evaluating the long-term thermal stability of a cable system is limited. This is because the time for the initiation of thermal instability of a cable system is a function of the initial soil moisture content which fluctuates seasonally. In order to apply this method, the test has to be performed when the moisture content of the soil is at its critical value. And this critical value, however, is extremely difficult to estimate. Thus a need exists for an identification system to evaluate the potential for thermal instability in any given soil type so that cable design engineers and operators can select and evaluate the cable backfills.

Thermally induced soil water movement in unsaturated soils is a complex phenomena. Many researchers have attempted to model the heat and moisture transport through porous media/7,8,9,10,11,12,13,14,15/. The model proposed by Philip and deVries which includes the interaction between the vapour and liquid phases/7/ showed good correlation with the laboratory results obtained by Cassel et al/16/.

Philip and deVries consider both the liquid and vapour phase transports of moisture in unsaturated soils under a thermal gradient. The governing equation for moisture movement under a thermal gradient in unsaturated soils can be written as:

$$\partial\theta/\partial t = \nabla.(D_T \nabla T) + \nabla.(D_\theta \nabla\theta) + \partial k/\partial z \quad \text{.....(1)}$$

$$c\partial T/\partial t = \nabla.(r\nabla T) - L\,\nabla.(D_{\theta vap} \nabla\theta) \quad \text{.....(2)}$$

where ∇T = thermal gradient

$\nabla\theta$ = volumetric moisture content gradient

θ = volumetric moisture content

T = temperature

k = hydraulic conductivity

c = volumetric heat capacity

r = thermal resistivity

L = latent heat of vaporization

$D_T = D_{Tliq} + D_{Tvap}$

D_{Tliq} = thermal liquid diffusivity

D_{Tvap} = thermal vapour diffusivity

$D_\theta = D_{\theta liq} + D_{\theta vap}$

$D_{\theta liq}$ = isothermal liquid diffusivity

$D_{\theta vap}$ = isothermal vapour diffusivity

Equation (1) and (2) are simultaneous equations describing coupled heat and moisture transfer in unsaturated soils. In view of the coupling effect between Equations (1) and (2) and the non-linear material properties involved, no exact solution can be obtained for most practical situations.

Based on the Philip and deVries model, a computer code, TRUCHAM (Transient Unsaturated Coupled Heat and Moisture flow code) was developed at Ontario Hydro/15/ which utilizes an integrated finite difference technique. It can accommodate a variety of linear and non-linear boundary conditions and material properties.

For most underground power cable systems, the value of the first term in the right-hand-side of Equation (2) is much larger than the value of the second term. Hence, neglecting the second term, the change in temperature can be expressed as:

$$c\partial T/\partial t = \nabla . (r\nabla T) \quad \text{.....(3)}$$

This equation indicates that the resulting thermal regime of a cable system is a function of the thermal resistivity of the soil, the heat input rate, the cable layout and the physical boundary conditions.

The thermal moisture migration model proposed by Philip and deVries states that moisture migration in a system not under the effect of gravity can be expressed as:

$$q/q_w = D_T \nabla T + D_\theta \nabla \theta \quad \text{.....(4)}$$

This equation indicates that the rate of moisture migration is governed by the thermal and moisture gradients in the system, the thermohydraulic properties of the soil expressed as D_T and $D\theta$. When there is no net moisture loss, the equation can be simplifed to;

$$\nabla T/\nabla\theta = D_\theta/D_T \quad \text{.....(5)}$$

Equations (3) and (5) provide basic information on the effect of thermal and hydraulic properties of soils on moisture migration and subsequent occurrence of thermal instability.

4.0 PROPOSED THERMAL STABILITY IDENTIFICATION SYSTEM

The moisture dependence of soil thermal resistivity provides one of the necessary conditions for the occurrence of thermal instability. The sufficient condition is the continuous moisture migration away from the cable. With the continuous moisture migration away from the cable, thermal instability will occur because the thermal resistivity of the soil decreases with time. For the proposed identification system, two sets of parameters are employed to characterize the necessary and sufficient conditions for the occurrence of thermal instability in a cable system. The first set of parameters are derived from the thermal resistivity versus moisture content curve and the second set are derived from the moisture migration equation.

The change in temperature in a cable system due to the change in moisture content of the soil adjacent to the cable is a function of the slope of the thermal resistivity versus moisture content curve of the soil. The thermal stability of a soil increases with the decrease in the slope of its thermal resistivity versus moisture content curve. The soil with a steeper slope is thermally less stable than the soil with a flatter slope. In this study, the slope of the thermal resistivity versus moisture content curve has been defined as the THERMAL INSTABILITY COEFFICIENT. The difference between the saturated moisture content and the critical moisture content is defined as the CRITICAL MOISTURE LIMIT. This limit value and the in situ moisture content of the soil together define the CRITICAL MOISTURE INDEX, which indicates the relative thermal stability of the soil. The ratio of the thermal resistivities of the soil at its complete dry state and its saturated state is defined as the THERMAL RESISTIVITY RATIO. This ratio provides an indication on the consequence of thermal drying of the soil on the performance of the cable system. The method of determining these indices is presented in Figure 3.

For two cable systems with identical thermal regimes, Equation (5) indicates that the system with a smaller D_θ/D_T value requires a higher moisture gradient or capillary return flow to balance the outward flow due to the thermal gradient. The D_θ/D_T value is most critical when the soil is at its critical moisture because thermal runaway or instability is incipient at that moisture content. Therefore, it is proposed that the

D_θ/D_T value at the critical moisture content, defined as the THERMOHYDRAULIC INDEX, is used as one of the factors to evaluate the thermal stability potential of the soil.

For a cable system with a constant rate of heat generation, the above proposed soil thermal index properties will provide valuable information for the cable design engineers and operators to evaluate the thermal stability of their cable systems.

5.0 ANALYSIS OF FIELD TEST RESULTS

The results of a field experiment performed by Adams and Baljet (1966) to examine the thermal instability phenomenon of a uniform sand is used to validate the Philip and deVries model to study the thermal instability phenomenon. The test site was located at the Toronto-Runnymede Transmission Station. The soil at this site is essentially granular material consisting of silty sand and gravel. The configuration of the cable and backfill trench is shown in Figure 4. The simulated cable consisted of a 9 cm diameter (OD) iron pipe heated internally by a mineral insulated heating cable and filled with an expanded cement grout. The pipe was placed in a trench approximately 60 cm wide and 120 cm deep. The uniform sand backfill was compacted to 97% standard Proctor density (dry unit weight of 1700 kg/m^3) at moisture content of 6.0 %. A string of 6 copper-constantan thermocouples were used to monitor the temperature within the system. The locations of the thermocouples are shown in Figure 4. With this arrangement of thermocouples, the soil thermal resistivity was determined for five concentric zones of increasing thickness. The thermal resistivity, thermal diffusivity and isothermal diffusivity versus moisture content relationships of the uniform sand determined from laboratory experiments are presented in Figures 5 and 6 respectively.

Figure 7 shows the time history of the average thermal resistivity of the soil within a concentric zone of 12 cm thickness around the cable. Considering that the thermal resistivity of the soil is highly dependent on its moisture content at the lower moisture range (Figure 2), the comparision between the thermal resistivity values estimated from the field measured temperature data and those predicted by the computer code is good. With this validation of the computer code by the field experiment, it is used for a parametric study to evaluate the relevance of the factors selected for the proposed thermal stability identification system.

6.0 PARAMETRIC STUDY

In order to access the validity of the proposed thermal soil identification system, the following cases were studied:

Case No.	Study Conditions q (W/cm)	thermal resistivity	isothermal diffusivity	thermal diffusivity	initial moisture content
1	0.49	Rt-1	DQ-1	DT-1	6.0%
2	0.98	Rt-1	DQ-1	DT-1	6.0%
3	0.98	Rt-2	DQ-1	DT-1	6.0%
4	0.98	Rt-1	DQ-1	DT-1	15.0%
5	0.98	Rt-2	DQ-1	DT-2	6.0%
6	0.98	Rt-2	DQ-2	DT-1	6.0%

The configuration of the modelled cable system was identical to the one used in the field experiment shown in Figure 4. The material properties used are shown in Figures 5 and 6. The results of this parametric study are presented in Figures 8 and 9.

The effect of the rate of cable heat generation is demonstrated by the results of cases 1 and 2 (Figures 8 and 9). By doubling the rate of cable heat generation, the resulting cable temperature is tripled at 240 hours. Such a large temperature difference obtained between cases 1 and 2 demonstrates the severe thermal runaway condition occurring in case 2.

The validity of the proposed thermal instability coefficient is illustrated by the results of cases 2 and 3. The thermal instability coefficients of cases 2 and 3 are $0.035^{o}C.cm/s$ and $0.057^{o}C.cm/s$ respectively. By increasing the thermal instability coefficient of the soil from 0.035 to 0.057, the cable temperature at 240 hours increased from $160^{o}C$ to $230^{o}C$ (Figure 9) and the moisture content of the soil adjacent to the cable decreased from 3.0% to 0.8%.

By comparing the temperature results of cases 2 and 4 (Figure 9), it can be seen that the initial moisture of the soil has a significant effect on the occurrence of thermal drying. This factor is included in the proposed critical moisture index. The critical moisture limits of both cases 2 and 4 are 13.6% and their critical moisture indices are 0.2 and 0.93 respectively. At 240 hours, the amount of moisture content depletion of the soil for cases 2 and 4 are 3% and 1.8% respectively. Although the difference in the amount of moisture depletion between the two cases is small, the temperature versus log-time curves showed in Figure 9 indicated that the thermal runaway phenomenon has occurred in case 2 but not in case 4. This was caused by the difference in the initial moisture content of the soils. For case 2, the initial moisture content of the soil is 6%. With a slight depletion in moisture content of the soil, large increases in thermal resistivity value will occur (Figure 5). For case 4, the initial moisture content of the soil is 15%. Thus a 9% depletion in moisture content is required before the occurrence of thermal instability. At 240 hours, the moisture content of the soil was changed from 15% to 13.2%. Within this range of moisture content the thermal resistivity of the soil remains unchanged. Therefore, no thermal runaway has occurred within the system.

In case 5, the thermal diffusivity value, D_T, used is one order of magnitude less than that of case 3. The results of the moisture plotted in Figure 8 indicates that at 240 hours, the amount of moisture loss in the soil adjacent to the cable is reduced with a decrease in the D_T value. A similar effect is seen by increasing the isothermal diffusivity value, D_θ, by an order of magnitude as in case 6. Thus by comparing cases 3, 5 and 6, it is seen that both D_θ and D_T influence the moisture depletion of the soil adjacent to the cable. In other words, the thermohydraulic coefficient, D_θ/D_T, is an important parameter required for identifying the potential for thermal instability in a cable system.

7.0 CONCLUSION

A thermal soil identification system is proposed to provide a rational basis for cable design engineers and operators to evaluate and select thermal backfills.

The proposed identification system has been validated by the results of a parametric study using the computer code TRUCHAM which is validated by a field experiment. It is shown that the thermal instability of the soil is a function of its thermal and hydraulic properties. The indices proposed to describe the thermal properties of the soils include the thermal instability coefficient, the critical moisture limit, the critical moisture index and the thermal resistivity ratio. The results of the parametric study indicate that the stability of the soils decrease with the decrease in thermal instability coefficient and decrease in critical moisture index.

The effect of the thermohydraulic properties on the thermal stability of soils is also considered in the proposed thermohydraulic coefficient of the soil. The larger the thermohydraulic coefficient, the more stable the soil is.

The thermal soil identification system proposed in this paper is in its rudimentary form. At present, it has been only applied to a uniform sand. It is anticipated that with the accumulation of a large data base

on the thermal and hydraulic properties of different soil types, a quantitative identification system can be developed.

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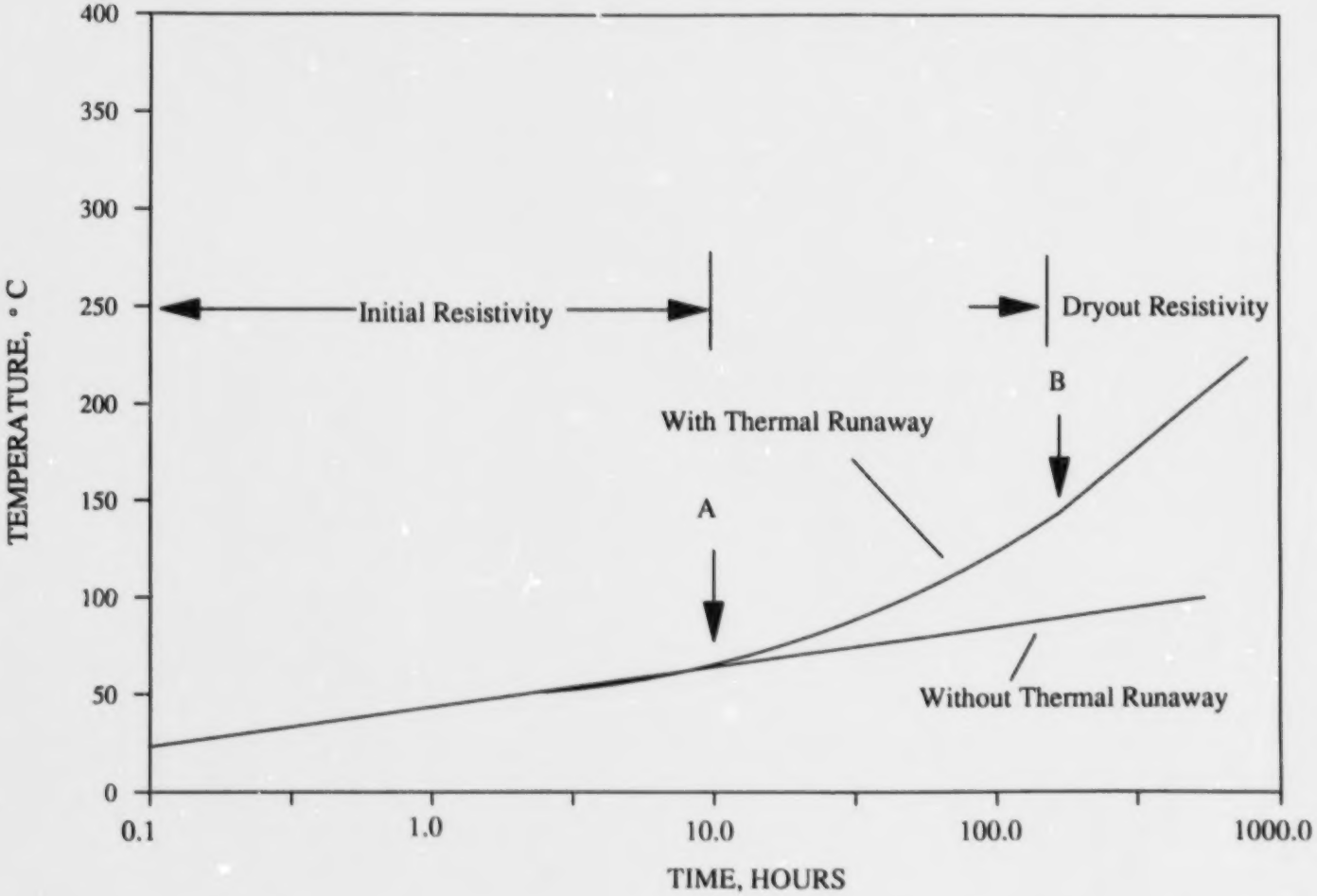

Figure 1 Temperature at Heat Source Versus Time Curves.

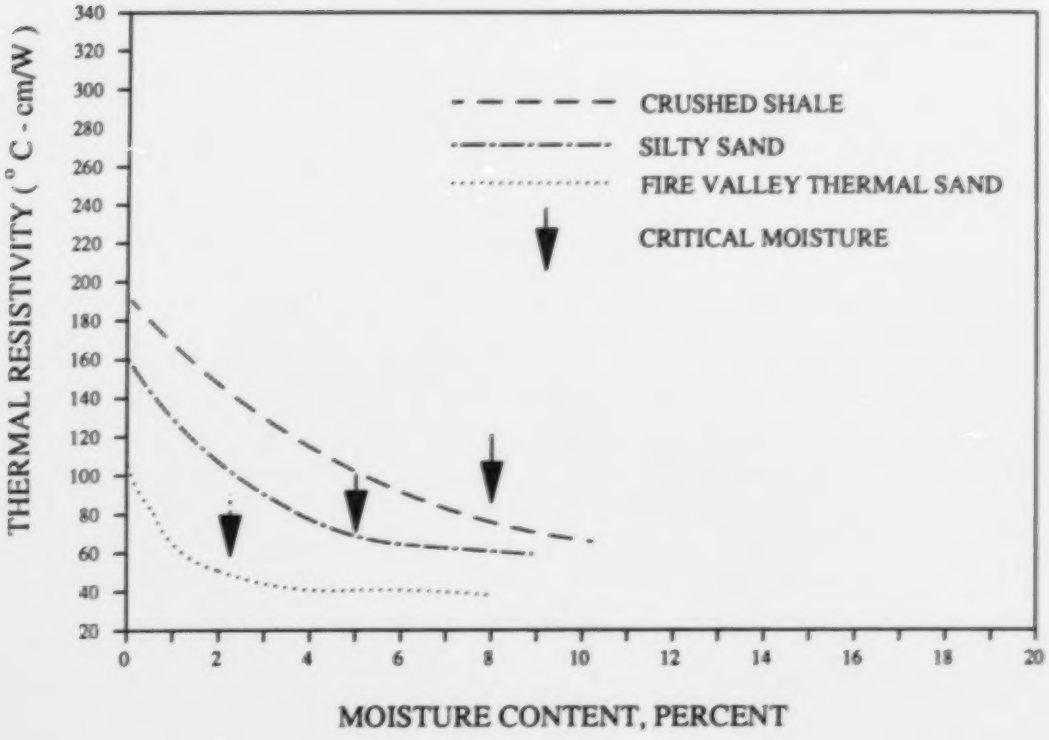

FIGURE 2 TYPICAL SOIL THERMAL RESISTIVITY VALUES.

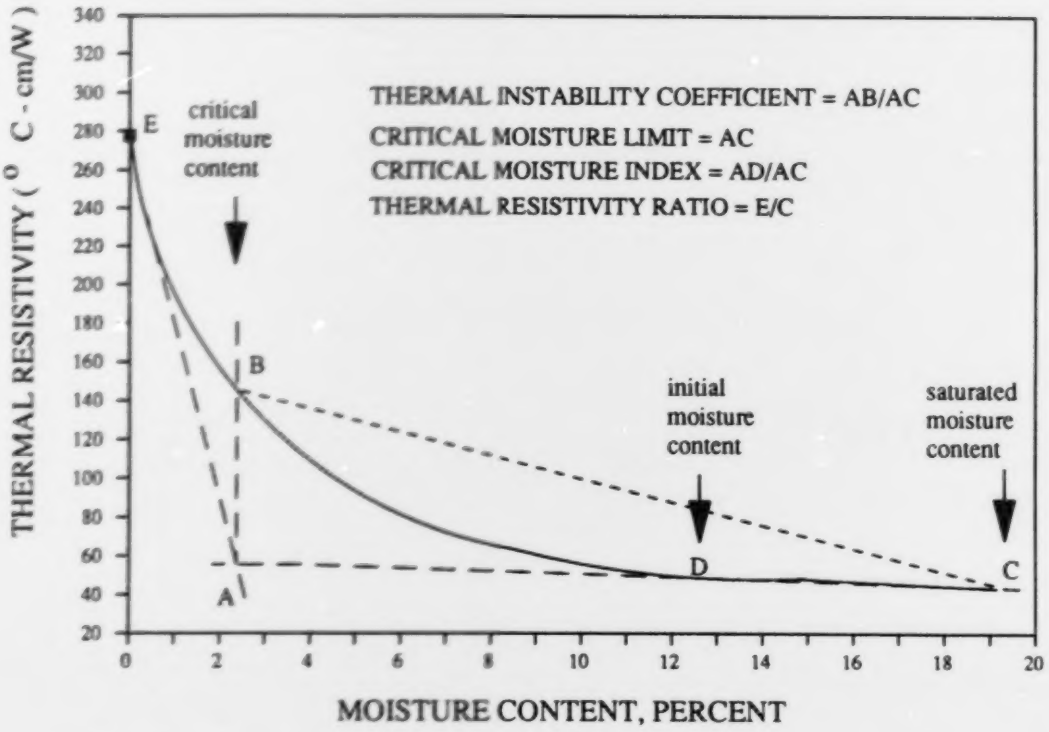

FIGURE 3 THE PROPOSED THERMAL SOIL STABILITY IDENTIFICATION SYSTEM.

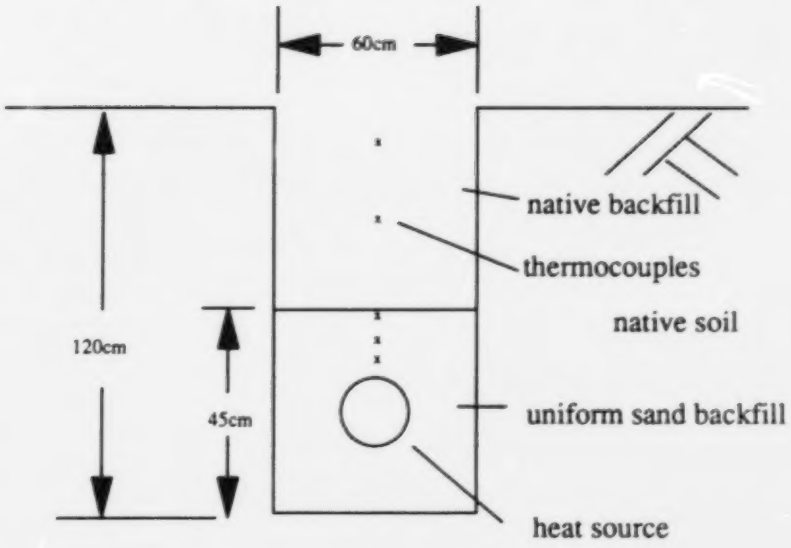

FIGURE 4 LAYOUT OF THE TEST-CABLE TRENCH.

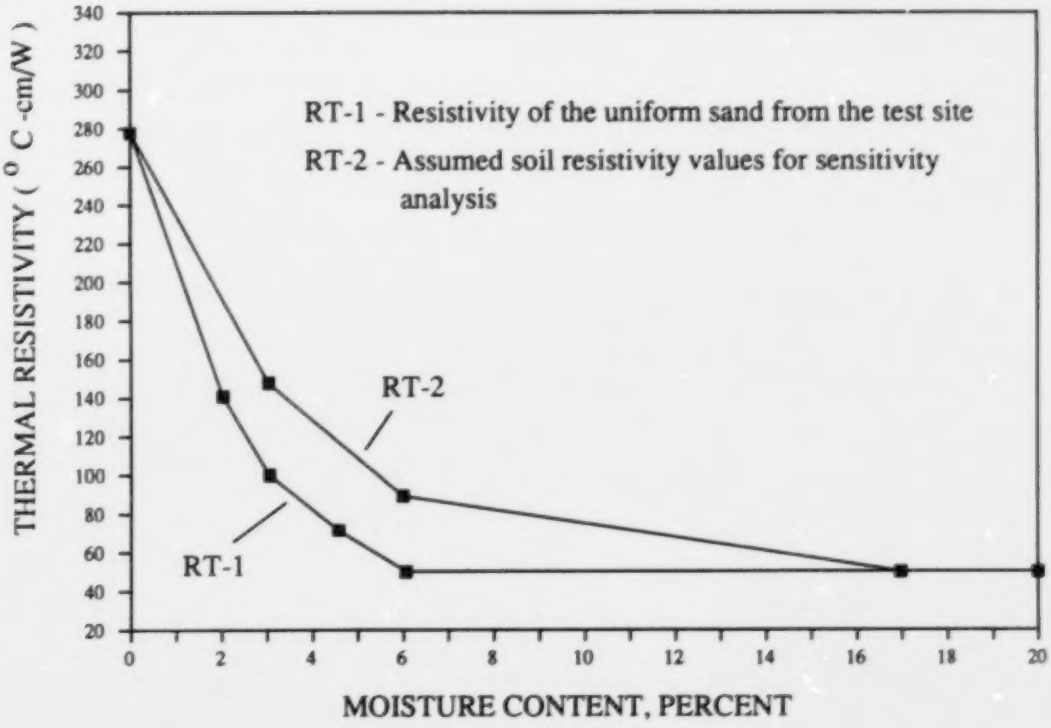

FIGURE 5 THE THERMAL RESISTIVITY OF THE SOILS.

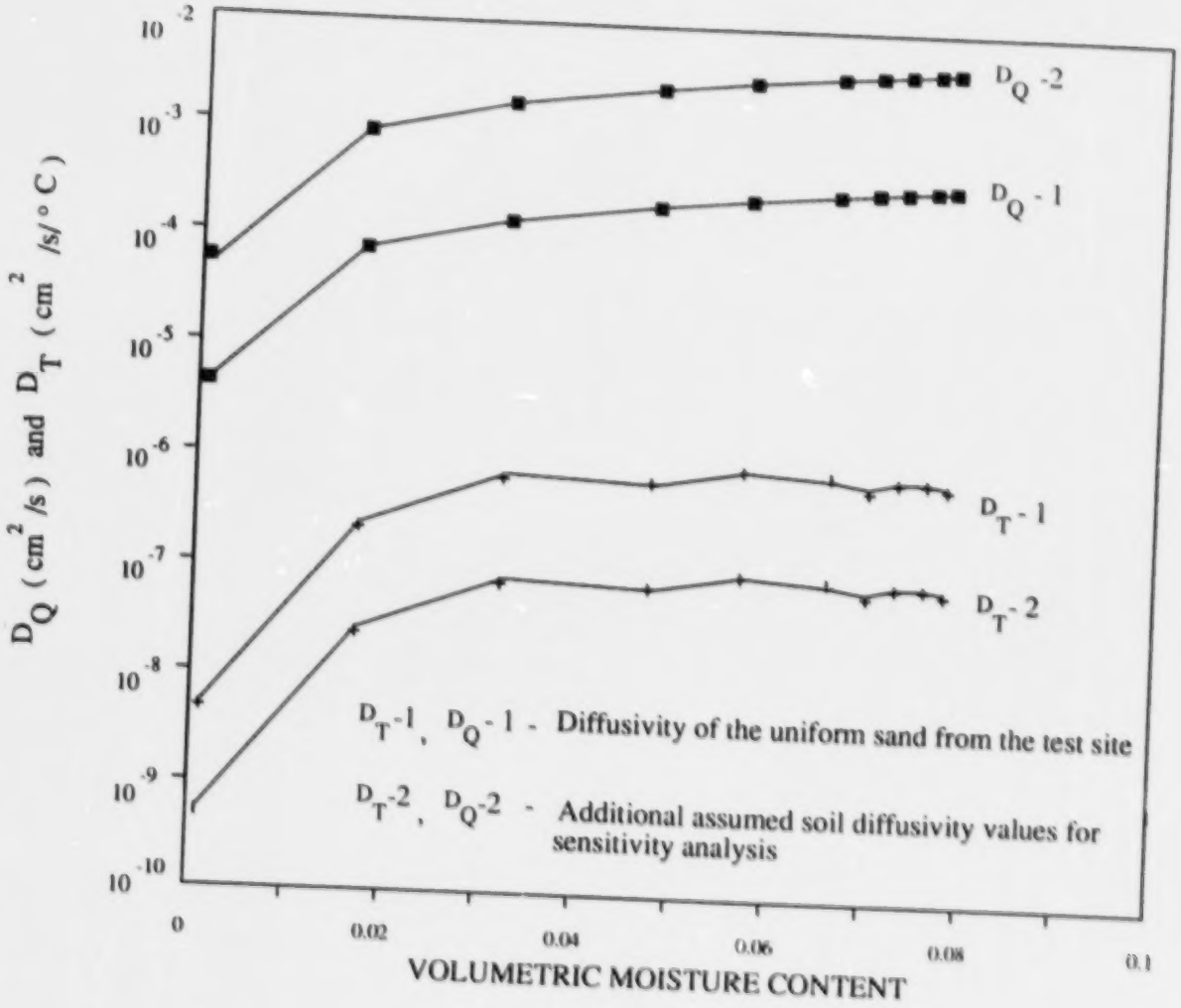

FIGURE 6 THE DIFFUSIVITY PROPERTIES OF THE SOIL USED IN THIS STUDY.

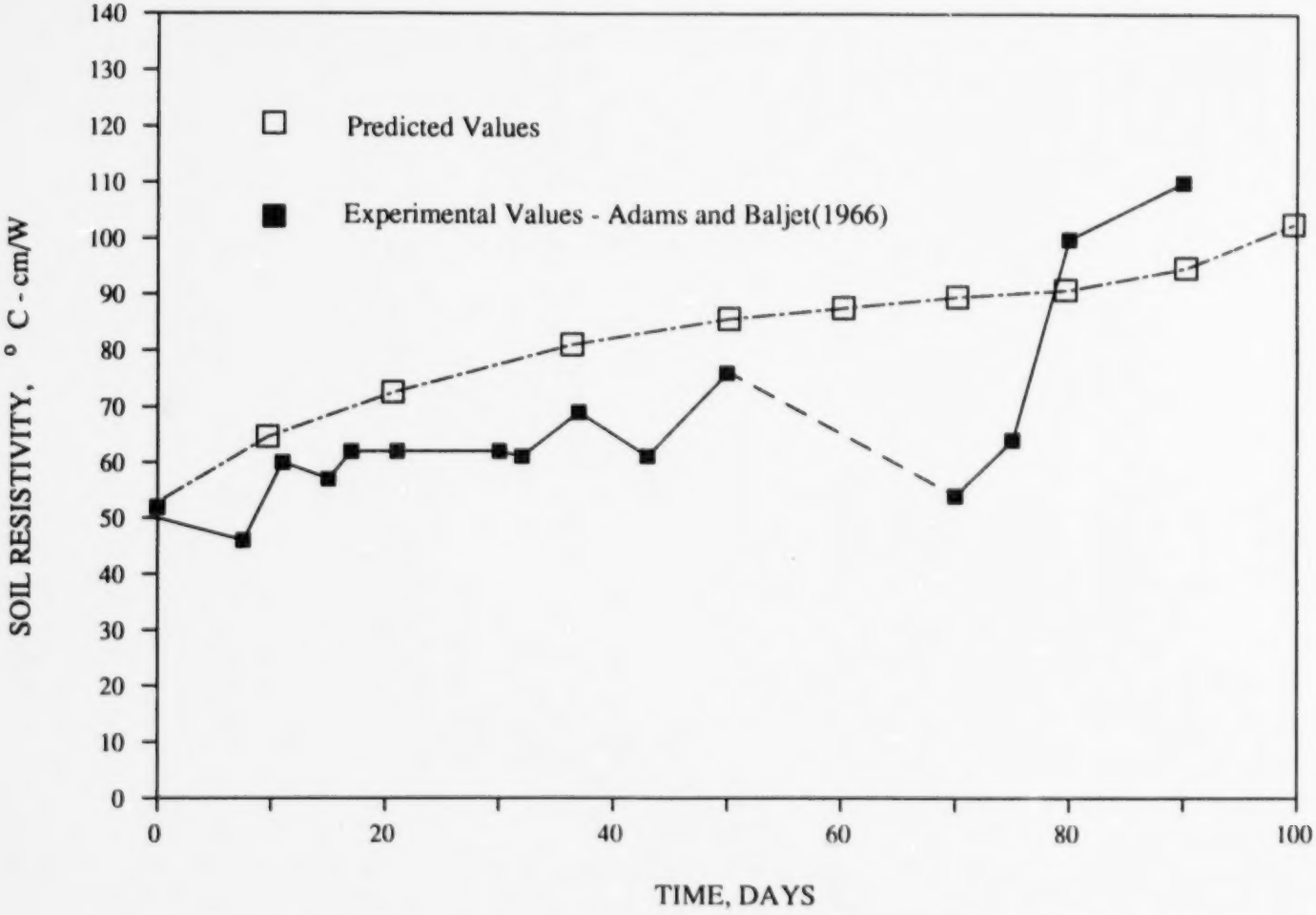

FIGURE 7 COMPARISON OF THE RESULTS ESTIMATED FROM FIELD RECORD AND PREDICTED BY THE COMPUTER.

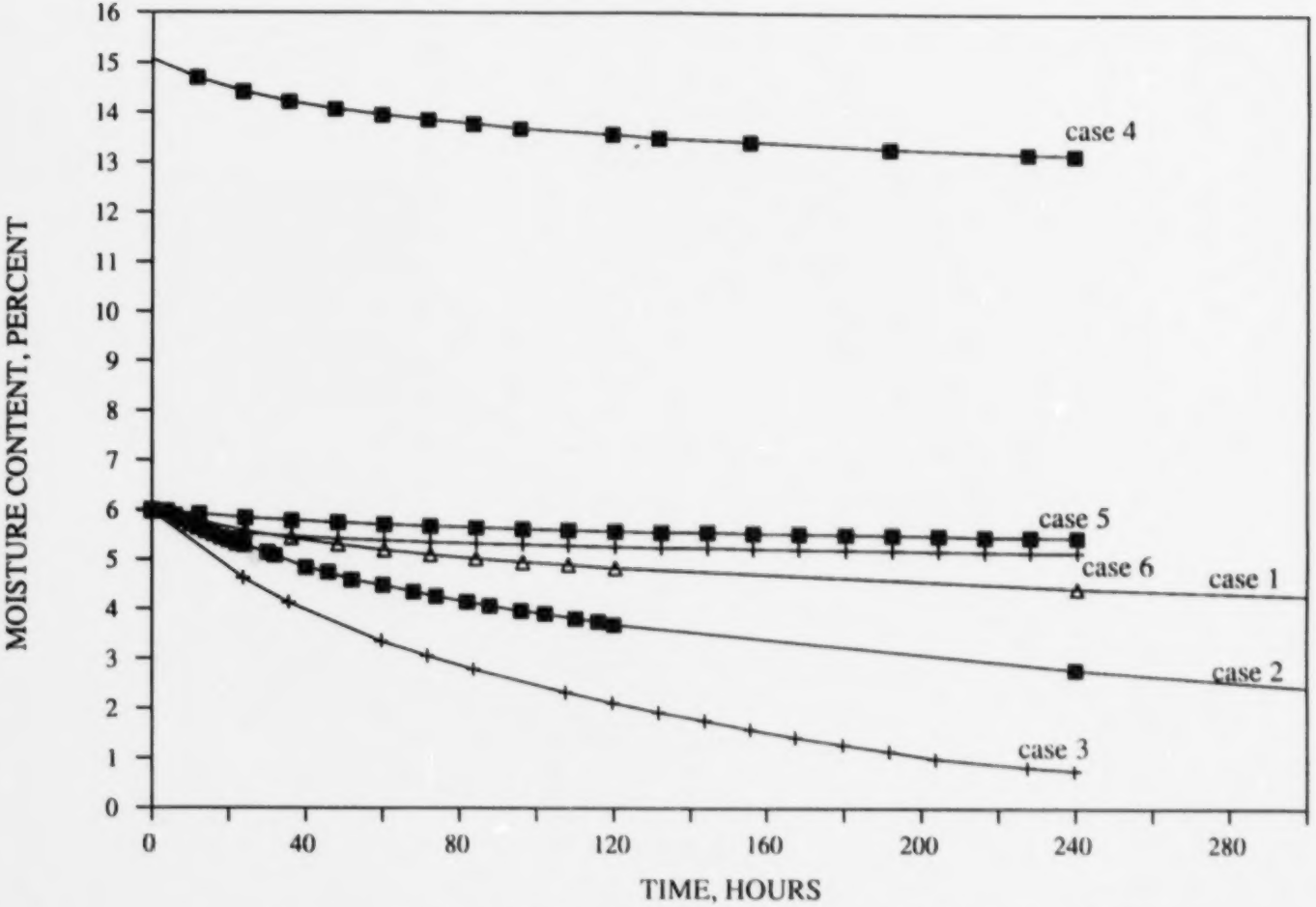

FIGURE 8 RESULTS OF THE PARAMETRIC STUDY - MOISTURE CONTENT OF THE SOIL ADJACENT TO THE CABLE VS TIME.

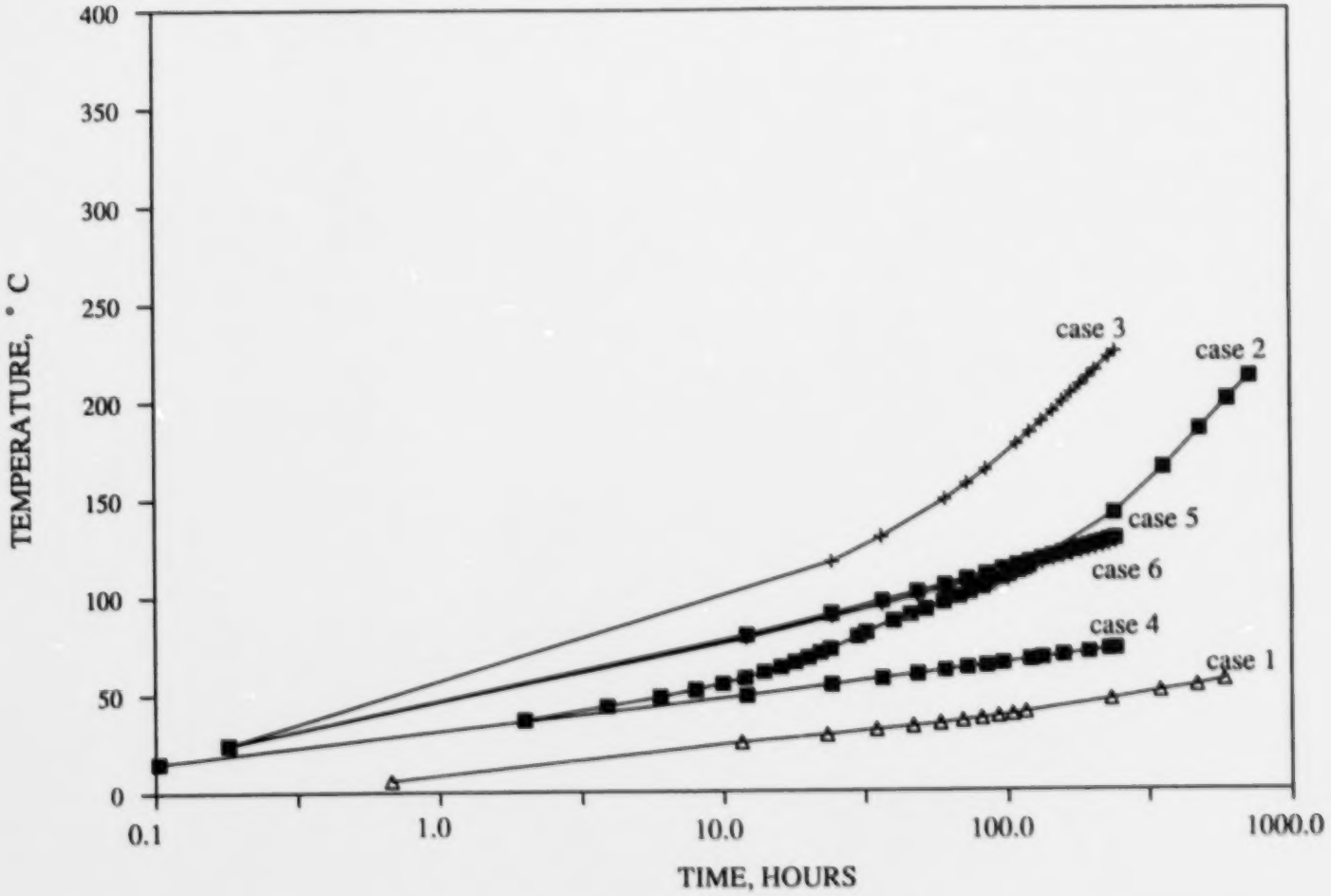

FIGURE 9 RESULTS OF THE PARAMETRIC STUDY - CABLE TEMPERATURE VS TIME.